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DYNAMIC RESPONSES OF INTERSPERSED RAILWAY TRACKS TO MOVING TRAIN LOADS

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This paper investigates novel dynamic phenomena of interspersed railway tracks. The interspersed method is commonly carried out by spot-replacing old timber sleepers with new concrete sleepers. Although this interspersed approach provides a short-term solution, such the method has a negative effect on the long-term performance of railway tracks. It is evident that the performance of interspersed tracks can quickly deteriorate after some years. As a result, this paper is the first to evaluate dynamic responses of the interspersed track caused by a moving train load in order to understand the root cause of swift track deterioration. Interspersed track models in three-dimensional space have been developed using a finite element package, STRAND7. The model was validated earlier with experimental results. Parametric studies have been conducted to evaluate dynamic responses of the interspersed railway tracks, including dynamic displacement, frontal uplift, rear uplift and accelerations of rail over sleeper, rail at midspan, sleeper at rail seat and sleeper at midspan. Dynamic amplification phenomena are highlighted as they convey a new insight into dynamic phenomena identifying the real source of track deterioration.

Keywords: interspersed track, timber sleeper, concrete sleeper, moving load, envelop analysis, dynamic response, dynamic factor, nonlinear transient analysis, tensionless support.

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1. Introduction

Conventional railway tracks are constructed using steel rails, sleepers, fasteners, ballast, and formation (capping layer over compacted soil). A critical review on the loading conditions acting on railway tracks for either passenger or freight trains shows that dynamic behaviour of a railway track is vital to understand the track dynamic responses to diverse loading conditions [1]. A critical loading condition, which often causes structural cracks in brittle sleepers, densifies and pulverises ballast support, is the large impact loads due to wheel/rail irregularities. For example, a common transient waveform pattern of wheel impacts due to an out-of-round wheel can be seen in Fig. 1. Clearly, the magnitude of the impact forces varies from 200kN to 400kN while the duration is ranging from 2 to 10 msec. Based on a transient pulse concept, these impact pulses are associated with the vibration excitation frequency range from 100 Hz to 500 Hz ($f = 1/T$: f is the frequency and T is the period). This frequency range can resonate with track components and lead to pre-mature damages. In the real world, wheel/rail interaction generates dynamic forces acting on a rail seat. The dynamic load patterns are dependent on train speed, track geometry, axle load, vehicle type, and wheel/rail defects or irregularities. Track engineers must consider the frequency ranges of static and dynamic loadings in life cycle asset maintenance and management of railway tracks with respect to critical train speeds and bespoke operational parameters [1-5].

Timber sleepers are still being used in railway track infrastructure all over the world. Their durability is estimated to be around 10 to 15 years depending on their applications, operation parameters, environmental factors and the level of maintenance quality. Partial replacement or spot replacement of timber sleepers by concrete

counterparts is an interesting concept to maintain track quality and improve short-term solutions that could be agile, cheap, effective and quick. This kind of spot replacement is usually adopted for the second or third class timber track or in some countries in the first-class main line. This solution is called “interspersed track”. In general, restricted train speeds are often imposed when track deteriorates to the condition below the base operation conditions (BOCs). By adopting the interspersed method, full operational speed can be allowed. Moreover, this approach strengthens for enhancement in ability to withstand high velocity operations or to restrain longitudinal rail forces preventing a track buckling [6-8]. Although partial replacement of aged, rotten sleeper is obviously highly more economical than completely track renewal or reconstruction, the interspersed track poses some disadvantages. Most often, the spot replacement concerns only on old, rotten timber sleepers and the new stiff concrete sleepers would be installed onto old and weakened foundation, which has been in services for a very long time. Moreover, the track stiffness of new track is inconsistent as the existing timber tends to be aging too. This track stiffness inconsistency and different track decay rate can be a reason of uneven settlement and foundation failure [9-13].

Owing to differential track stiffness, deterioration processes, track component durability and operational parameters, many patterns of interspersed railway tracks have been introduced i.e. 1 in 2, 1 in 3, 1 in 4 and so on (which means that there is 1 concrete sleeper in every indicated number of sleeper; for instance, 1 in 4 means 1 concrete sleeper in every 4 sleepers including the concrete itself). This type of railway track mainly exists in a rail network with low operational speeds. A key reason is that this type of track has various flaws derived from how it is built. These can impair the long-term performance

of interspersed railway tracks as shown in Figure 1 [13]. Figure 1 shows the conditions of interspersed railway tracks in low-speed operation (<25 km/h). The tracks have been commissioned between 2006 and 2008 and have served as a main high-speed link to maintenance junctions. The photos were taken in April 2016 during a site visit.

The serviceability limit state of the railway track has become the governing criteria for sleepers made of different material properties in the existing aged track systems. It is important to note that a general recommendation (e.g. by Australian Office of Transport Safety Investigations) is to perform concrete sleeper installation only ‘in-face’ (i.e. the practice of installing the same sleeper type continuously rather than interspersed with other sleepers in between, also referred to as ‘on-face’) [11-13]. This paper aims at investigating the dynamic responses of the interspersed railway tracks to a moving train envelope. Based on critical literature review, this research has never been presented in open literature [14-21]. A class of two-dimensional interspersed track models was created using Timoshenko beams in a finite element package, STRAND7. Dynamic displacement, frontal uplift, back uplift and accelerations have been evaluated at rail over sleeper, rail at midspan, sleeper at rail seat and sleeper at midspan. Dynamic amplification phenomena are then highlighted in this paper. The insight into the interspersed track responses will help rail track engineers to enable a truly predictive maintenance and improve the reliability of infrastructure asset maintenance and management.

2. Track model

A two-dimensional Timoshenko beam model was previously developed and found to be one of the most suitable options for modeling concrete sleepers [22-25]. In this study, the

finite element models of railway tracks have been developed and calibrated against the numerical and experimental modal parameters [25-27]. Figure 2 shows the finite element models in three-dimensional space for an in-situ railway track with different types of sleepers. Using a general-purpose finite element package STRAND7 [28], the numerical model included the beam elements, which take into account shear and flexural deformations, for modeling the sleeper and rails. Each sleeper consists of 60 beam elements and each rail consists of 200 beam elements. The 60kg rail cross section and sectional parameters (Area: 17,789.9 mm²; Second moment of Area: 43.2 x10⁶ mm⁴) were used in accordance with Australian Standard AS1085.1 [29]. The trapezoidal cross-section was assigned to the concrete sleeper elements in accordance with the standard medium duty sleepers (204 mm top-wide x 250 mm bottom-wide x 180 mm deep) [30-31]. The rectangular cross-section was assigned to the timber sleeper elements in accordance with the standard timber sleepers (230 mm wide x 130 mm deep) used in NSW [32]. The rail pads at railseats were simulated using a series of spring-dashpot elements. The distance offset between rails and sleepers was set to 100mm to more clearly illustrate the track behaviours. This setup does not affect the numerical results [27-28]. In this study, the stiffness and damping values of high density polyethylene (HDPE) pads were assigned to these spring-dashpot elements [26]. The support condition was simulated using the nonlinear tensionless beam support feature in STRAND7 [28]. This attribute allows the beam to lift over the support while the tensile supporting stiffness is omitted. The tensionless support option can correctly represent the ballast characteristics in real tracks [27-28]. The sleepers are connected to both rails using spring-dashpot elements with hinge nodes at railseats. The displacement restraints have

been applied to the rail ends. The experimental modal testing was first performed to identify structural parameters of the sleepers. Then, the finite element model was developed using available data from the manufacturer. The model was then updated through the comparison of modal parameters. Table 1 shows the geometrical and material properties of the finite element model. Based on previous studies [20-27], effects of length and boundary of track in this study (18 bays or 10.8 m) on the computation and the frequencies of interest are negligible. These data have been validated and the verification results were presented elsewhere [27].

In total, 5 types of interspersed tracks have been established for dynamic investigations, including pure concrete, pure timber, 1 in 2, 1 in 3 and 1 in 4. The ‘1 in 2’ means concrete and timber sleeper placed alternately. The ‘1 in 3’ implies that one concrete sleeper installed in two adjacent timber sleepers, and the ‘1 in 4’ means one concrete sleeper installed with three adjacent time sleepers. All types of track are shown in Figures 2. Engineering properties of each element are tabulated in Tables 1 – 5. All dimensions are given in millimeters. The partial support condition, which has been reported to be more suitable for standard gauge tracks [30], has been adopted for this study (as illustrated in Figure 2f). Spring – dashpot model of rail pad is presented in Figure 2g. For the envelope study, four separated forces with a constant magnitude of 100kN have been used to imitate the loading condition of a passenger train bogie (2 per each rail, 2 meters apart). This load magnitude has been used for benchmarking purpose [33-36]. The non-dimensional analyses have then been carried out to investigate the dynamic amplification over train speed and over frequency domain.

3. Results

The Linear Static Solver of Strand 7 has been used to solve for the static behavior of railway tracks. For the static analysis, the position of axle loads coincides with the axle of the model. The Nonlinear Transient Solver is then used to solve the dynamic cases. For the dynamic analysis two load paths with the moving load envelope have been established. The dynamic analyses are been conducted for a range of train speeds from 10km/h to 120km/h with a step of 10km/h. To appropriately take into account the moving loads, the analysis duration (iteration time steps) has been set adaptively in order to enable entire load pass-bys in the models. Table 6 displays the time steps of calculations in each case. Vertical track displacements, front and back uplifts and dynamic accelerations of the track are investigated under both the static and the moving load conditions. The emphasis of these numerical simulations is placed on the dynamic responses at critical locations, including rail over sleeper, rail at midspan, sleeper under rail and sleeper at midspan. Dynamic amplification factors are calculated as a ratio of dynamic over static response. Typical dynamic deformation of a railway track under the moving load can be demonstrated in Figure 3. It can be observed that right under the trainload, the rails and sleepers flex due to positive bending whilst there exist uplift actions in front of and at rear of the bogie load. The front and back (or rear) uplifts of rails can be noticed in all dynamic simulation cases. In addition, when the load moves pass by a position, all numerical simulations reveal that the rail uplifts excite the sleepers upward and also result in amplified vertical vibrations and uplift displacements of railway

sleepers. The sagging and hogging behaviors of sleeper component could then be pronounced by the dynamic responses of interspersed tracks.

Figure 4 demonstrates the dynamic effects of interspersing methods coupled with train speeds on the maximum displacement responses of rails and sleepers. Considering the rail responses over the sleepers, it is clear that timber sleepered tracks deform vertically higher than interspersed or concrete sleepered tracks. The timber sleepered tracks tend to resonate with the train speeds from 90 to 100 km/h. On the other hand, concrete sleepered tracks seem to resonate with the train speed of around 70 km/h. Based on the front uplift of rails, it can be observed that the interspersed track poses a significantly larger upward displacements, in comparison with either timber or concrete sleepered tracks. On average, timber sleepers in the interspersed tracks displace at larger amplitude compared with concrete counterparts. This implies a considerable pulverization and densification of ballast and supporting formation under timber sleeper zone from the train pass-bys. This damage has in fact been evident from the site visit where track mud pumping (formation stress failure) has been observed right under timber sleepers in the interspersed tracks.

In addition, when consider the dynamic responses of sleeper at mid span, inverse behavior can be observed. The concrete sleepers in the 1:4 interspersed tracks hog largely under the moving loads compared with other sleepers. This could induce ballast dilation and cause center-bound failure in the future. Also, it can be seen that the timber's elasticity has yielded well stress redistribution along the sleeper, resulting in less hogging behavior of the timber sleepers.

Accelerances of rails and sleepers have been evaluated as shown in Figure 5. It can be found that rails, at both over sleeper and in between sleepers, in the concrete sleepers track vibrate at the lowest amplitude of acceleration. This is because concrete sleepers usually have higher mass that could pin down the rails and inversely proportionate to accelerations. It is noted that the level of acceleration of rails of interspersed and timber sleepers tracks is significantly higher than that of concrete sleepers tracks. However, it can be observed that timber component poses an anti-resonance associated with a train speed of 90 km/h. In addition, the accelerations of sleepers at rail seat and at mid span clearly demonstrate a similar trend. The timber sleepers tend to accelerate faster and greater due to its light weight. This causes enduring track vibrations and triggers systems oscillations. This dynamic behavior coincides with the observed location where ballast dilates or spreads out around the edge of sleepers, especially around concrete sleepers in the interspersed tracks. Without appropriate track maintenance, ballast dilation can undermine such the location that the track section loses lateral resistance and will be prone to track buckling under extreme heat condition.

Dynamic amplification factors of rails and sleepers are illustrated in Figure 6. It clearly shows that concrete has poor performance in dampening rail vibration responses. However, higher concrete density helps to stabilise railway tracks by reducing uplift dynamics of the rail over the sleepers and of the rail at mid span. When consider the sleepers at rail seat (sleeper under rail), the interspersed track could better provide anti-resonant mechanism that counter balance the dynamic amplification by its unbalanced mass systems (different sleeper masses). However, the anti-resonant benefit could appear only for the vertical downward responses. It is found from all cases that the very

dominant uplift responses of all sleepers in the interspersed tracks are highly likely to induce damages on track components due to their ability to amplify the sleeper uplift responses at the railseats. Similar trend can also be observed on the dynamic responses of the sleepers at mid span. However, it should be noted that the concrete sleeper in ‘1 in 4’ interspersed track suffers the most from negative bending moment, which could later cause center-bound problem (where sleeper flex upward and cracks develop from the top surface).

4. Conclusion

Interspersed tracks where spot replacement of sleeper exists can still be found in many countries around the world. Such practice can cause excessive track maintenance over time. This is because a cluster of timber sleepers with mixed quality could deteriorate faster than the others and the replacement by concrete sleepers could induce track stiffness inconsistency and aggravate loading conditions acting on the track. This paper is found to be the first to investigate dynamic responses of the interspersed track caused by a moving train load in order to understand the root cause of rapid track deterioration. A finite track models in three-dimensional space have been established and validated. The parametric studies have revealed the key insights into the actual source of track deterioration, including:

Rails

Maximum displacements of the rail are the smallest in the concrete sleepered tracks. However dynamic amplification factor is the greatest for this type of track. On the other hand, dynamic uplift amplification factor is the lowest in the concrete sleepered track due

to its higher density. In timber and interspersed tracks, the uplift responses of rails can be pronounced and considered as the key source that triggers other mode of track vibrations, which could induce ballast pulverization, ballast dilation, and uneven densification.

Sleepers

Maximum displacement responses of the sleeper at railseat are smallest in the concrete sleepers tracks. However, it is found that dynamic amplification factors in these cases are the largest. Dynamic uplifts of sleeper at railseat in interspersed tracks can be significantly amplified especially for the concrete sleepers. Similar trend can also be observed for the mid span of concrete sleepers. Importantly, it is clear that the timber sleepers in the ‘1 in 3’ and ‘1 in 4’ interspersed tracks suffer exceptionally from the moving train loads. Not only can the dynamic uplift of the timber sleepers break ballast gravels, but it can also induce additional magnitude of stress wave onto formation and result in formation failure. This is evident from the actual field inspection where mud pumping often initiates under the timber sleepers in the interspersed tracks.

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Table 1 Engineering properties of rail used in the modeling

Parameter lists		
Length	$l_r=10.8$	m
Gauge	$g=1.5$	m
Modulus	$E_r=2.0000e5$	MPa
Poisson's ratio	$\nu_r=0.25$	-
Density	$d_r=7850$	kg/m^3

Table 2 Engineering properties of rail pad used in the modeling

Parameter lists		
Rail pad stiffness	$k_p = 17$	MN/m

Table 3 Engineering properties of concrete sleeper used in the modeling

Parameter lists		
Length	$l_s=2.5$	m
Spacing	$s=0.6$	m
Modulus	$E_s=3.7451e4$	MPa
Shear modulus	$G_s=1.0896e4$	MPa
Density	$d_s=2740$	kg/m^3

Table 4 Engineering properties of timber sleeper used in the modeling

Parameter lists		
Length	$l_t=2.5$	m
Spacing	$s=0.6$	m
Modulus	$E_t=1.2300e4$	MPa
Poisson's ratio	$\nu_t=0.00$	-
Density	$d_t=1250$	kg/m^3

Table 5 Engineering properties of concrete sleeper used in the modeling

Parameter lists		
Ballast stiffness	$k_b = 13$	MPa

Table 6 Time of calculation for Nonlinear Transient Solver

V [km/h]	TOTAL STEPS	TIME STEP [s]	TIME [s]
10	5250	0,001	5,250
20	3250	0,001	3,250
30	2250	0,001	2,250
40	1500	0,001	1,500
50	1250	0,001	1,250
60	1000	0,001	1,000
70	1000	0,001	1,000
80	1000	0,001	1,000
90	1000	0,001	1,000
100	1000	0,001	1,000
110	1000	0,001	1,000
120	1000	0,001	1,000

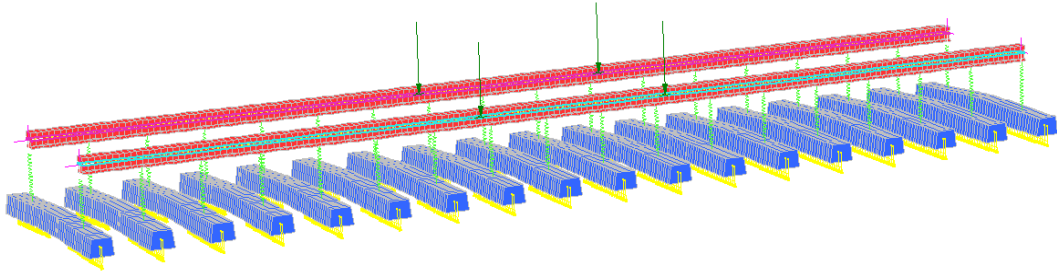


(a)

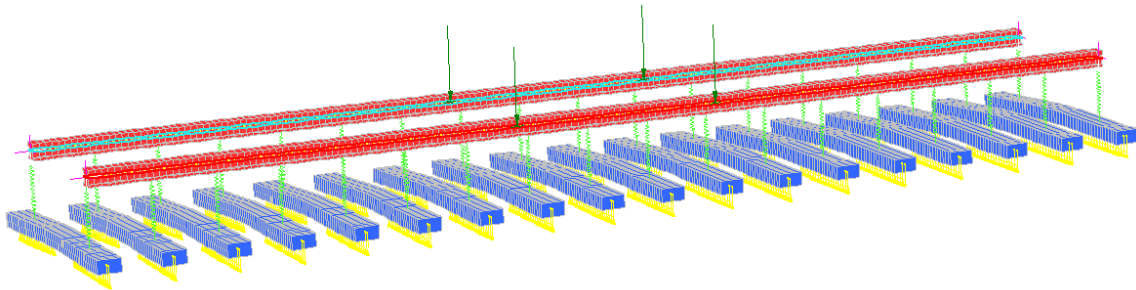


(b)

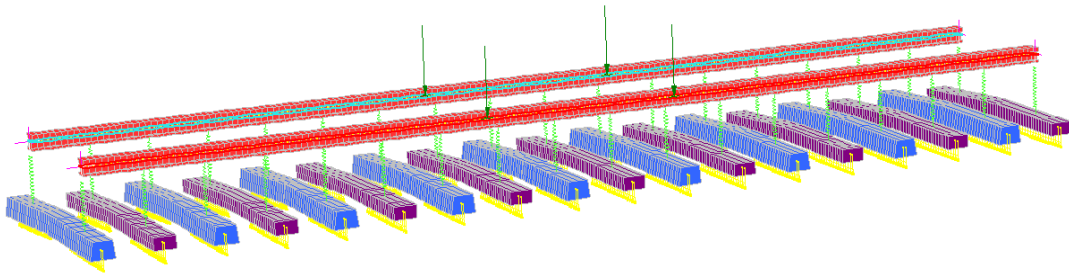
Figure 1: Deteriorated interspersed railway track (a) Top: mud pumping, and (b) Bottom: ballast pulverisation and ballast dilation



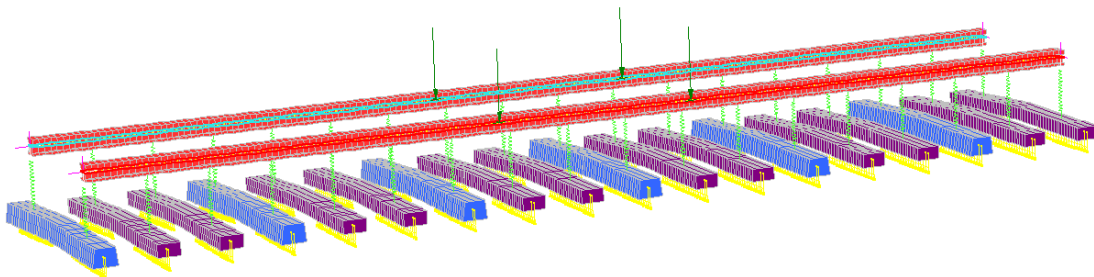
a) The model of concrete track



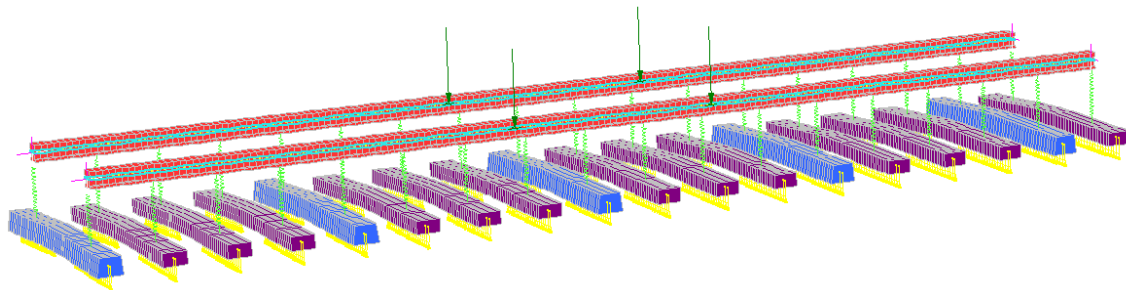
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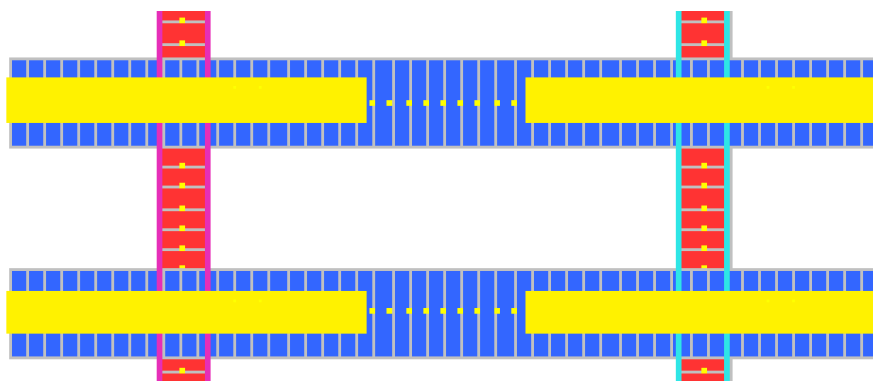
c) The model of 1 in 2 track



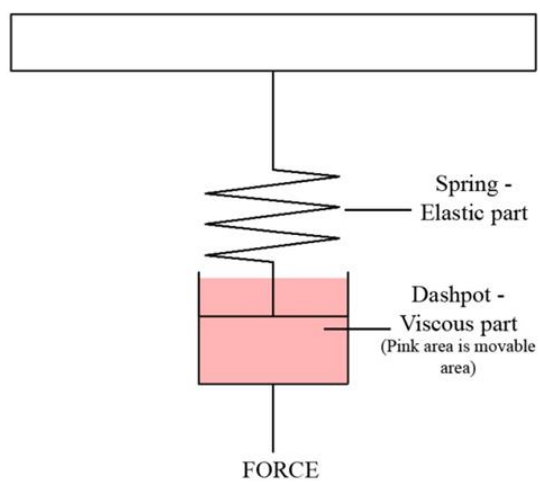
d) The model of 1 in 3 track



e) The model of 1 in 4 track



f) The support of sleepers



g) Spring – dashpot model of rail pad

Figure 2 Dynamic track models

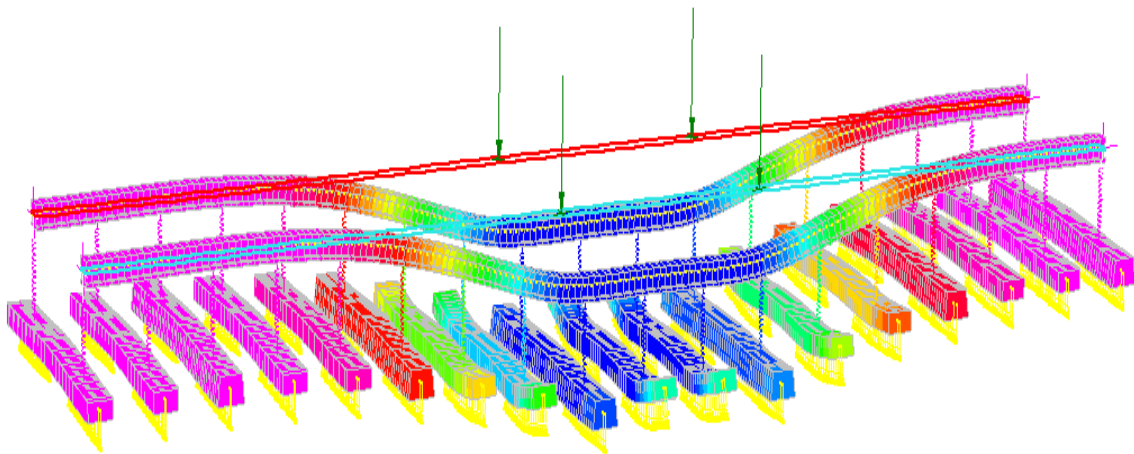
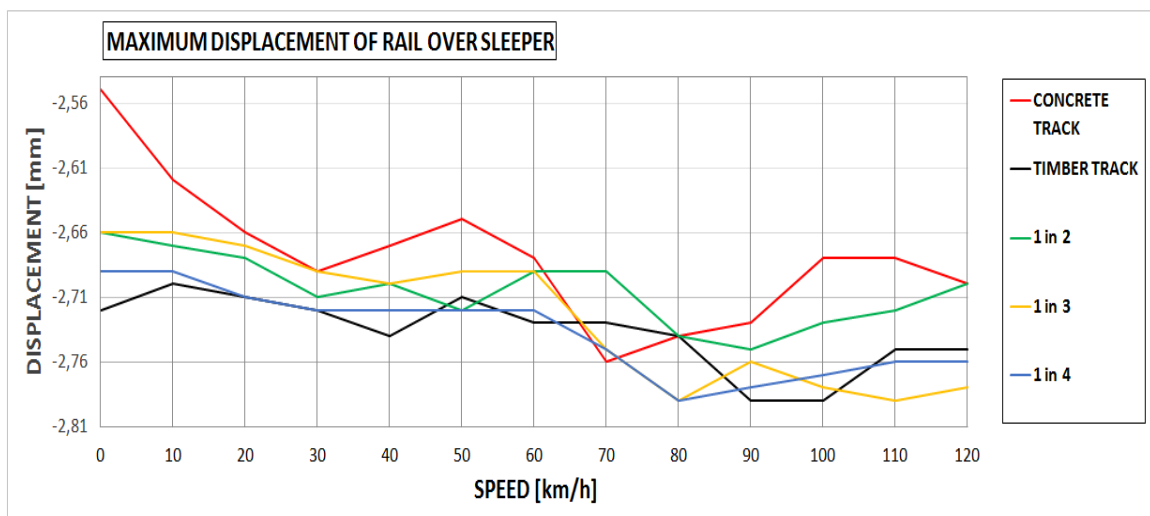
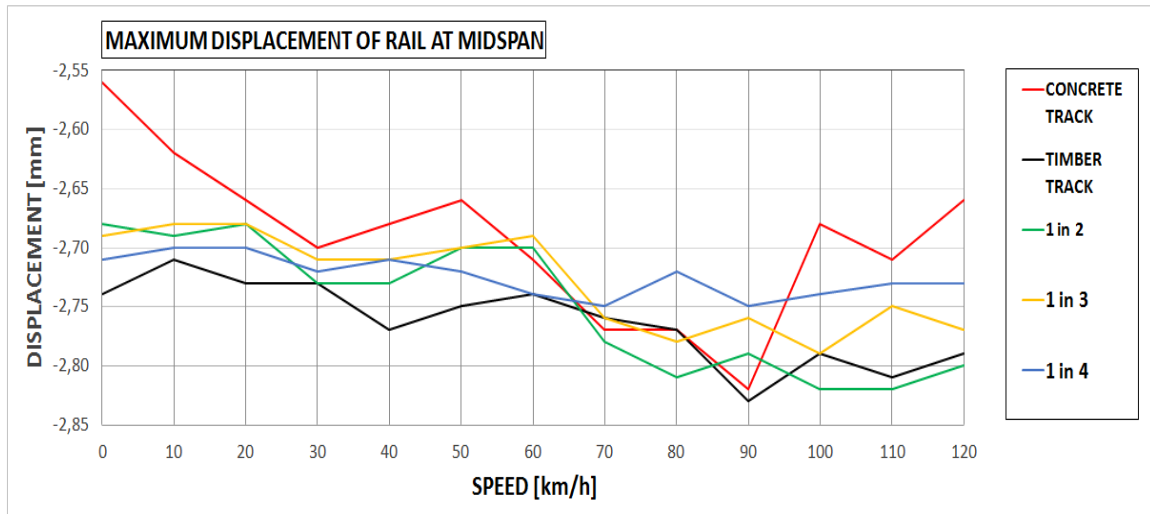


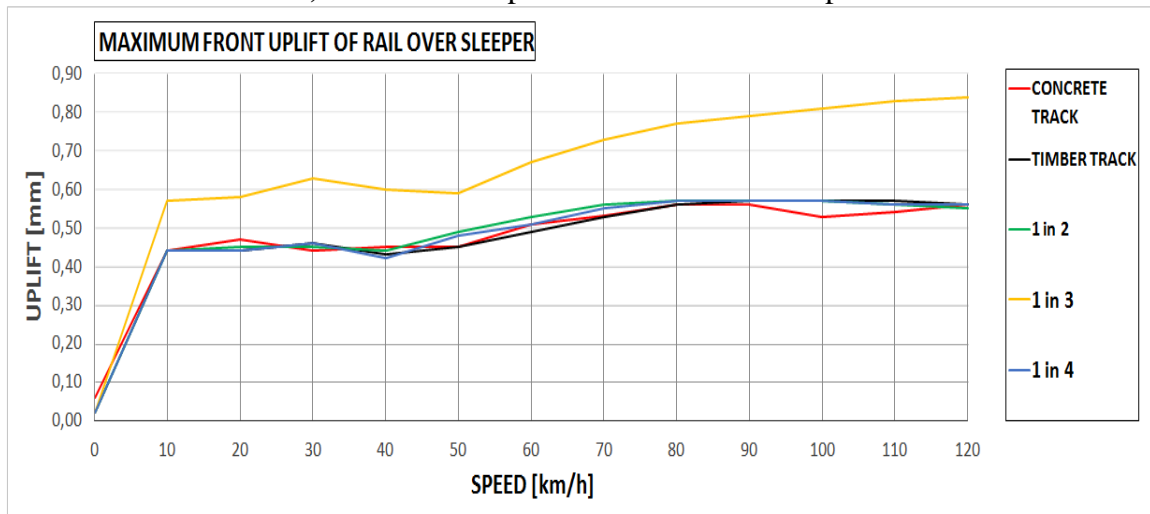
Fig. 3 The example of the track's deformation under the moving load



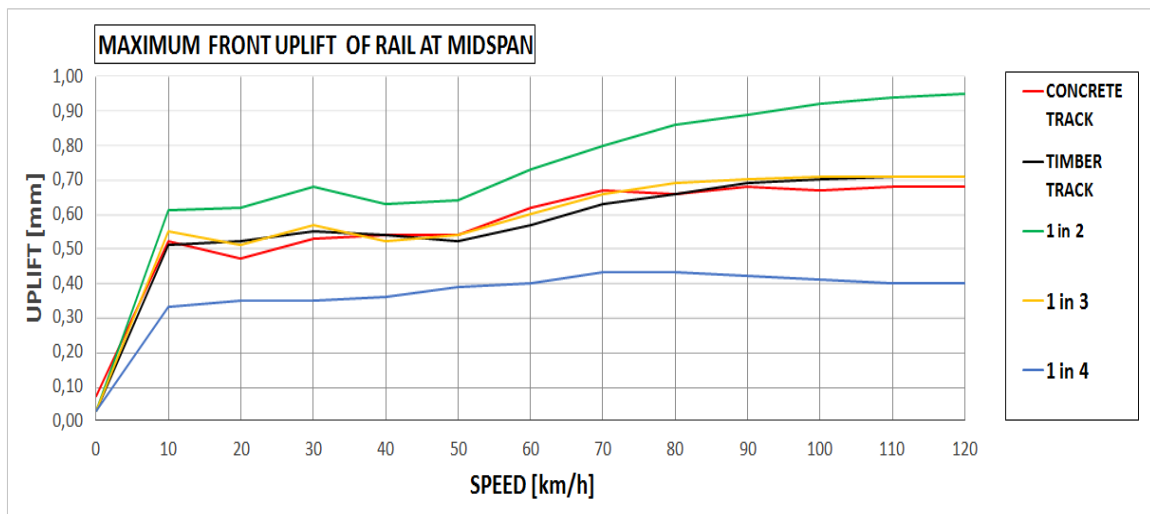
a) Maximum displacement of rail over sleeper



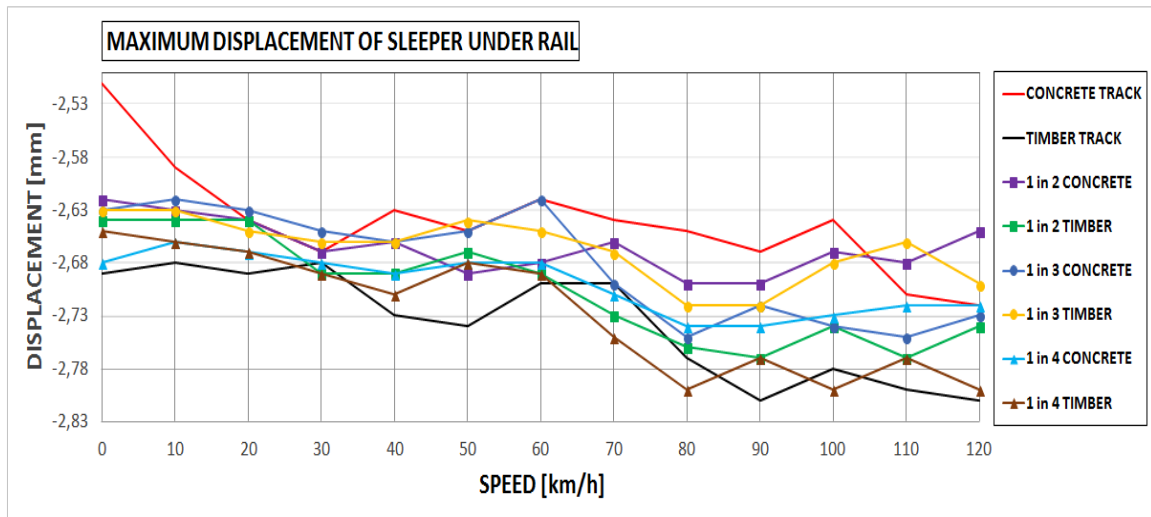
b) Maximum displacement of rail at midspan



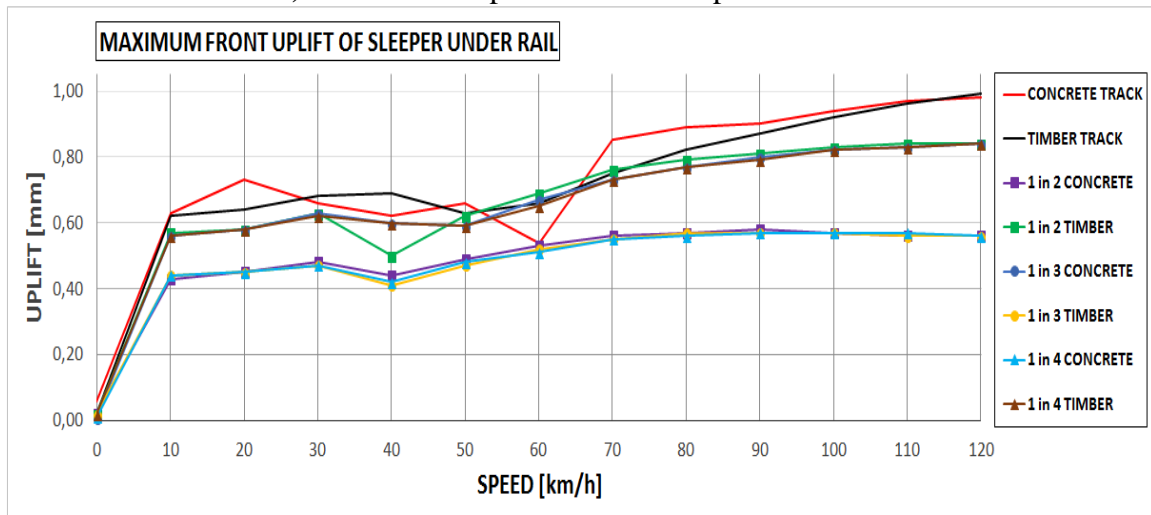
c) Maximum front uplift of rail over sleeper



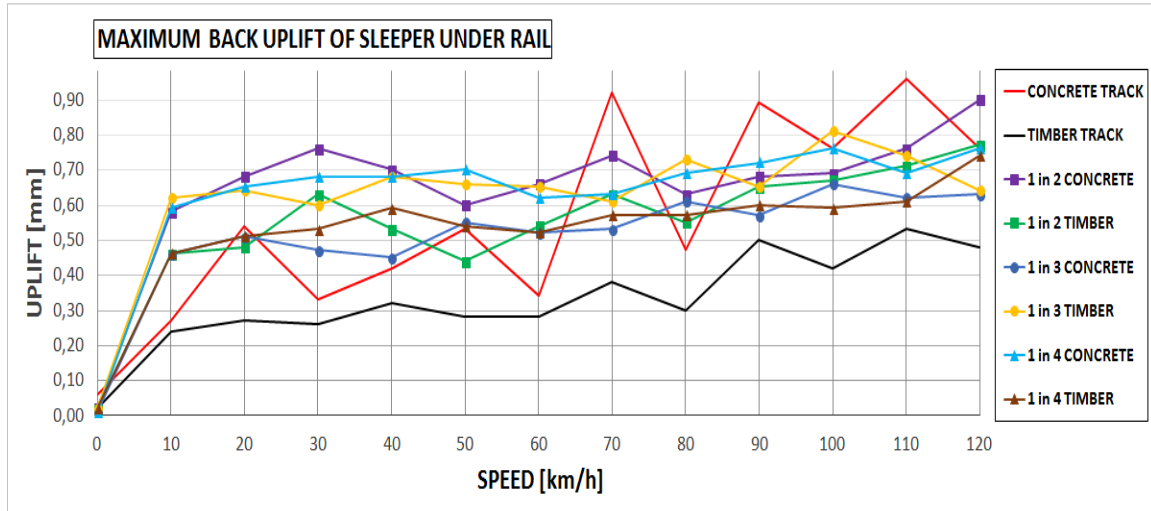
d) Maximum front uplift of rail at midspan



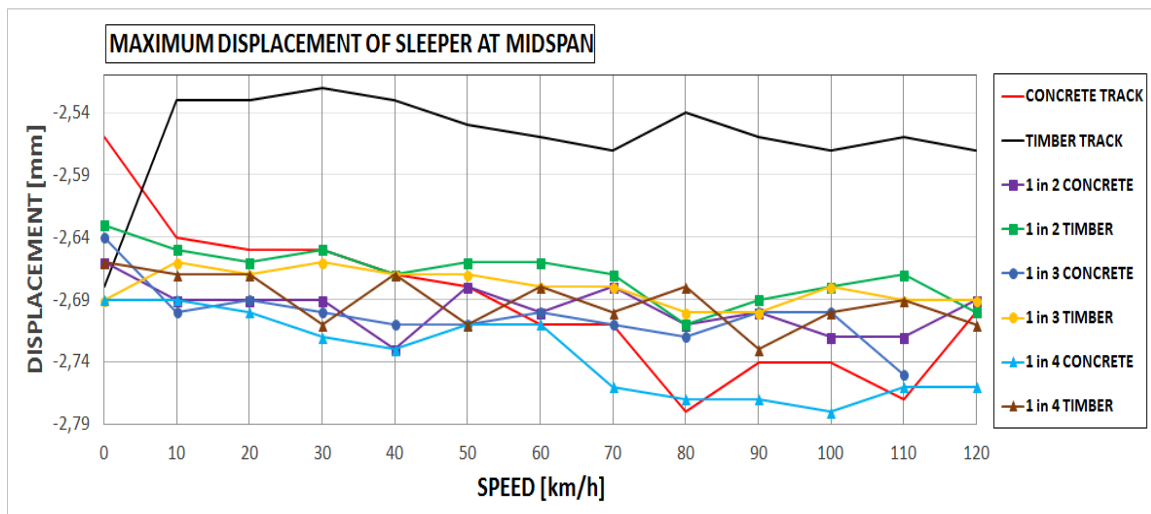
e) Maximum displacement of sleeper under rail



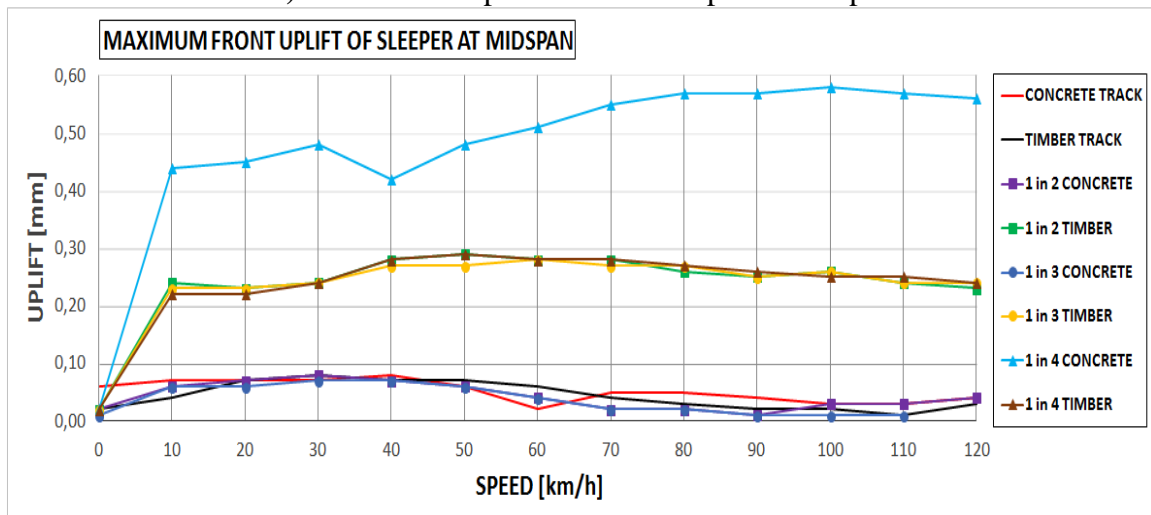
f) Maximum front uplift of sleeper under rail



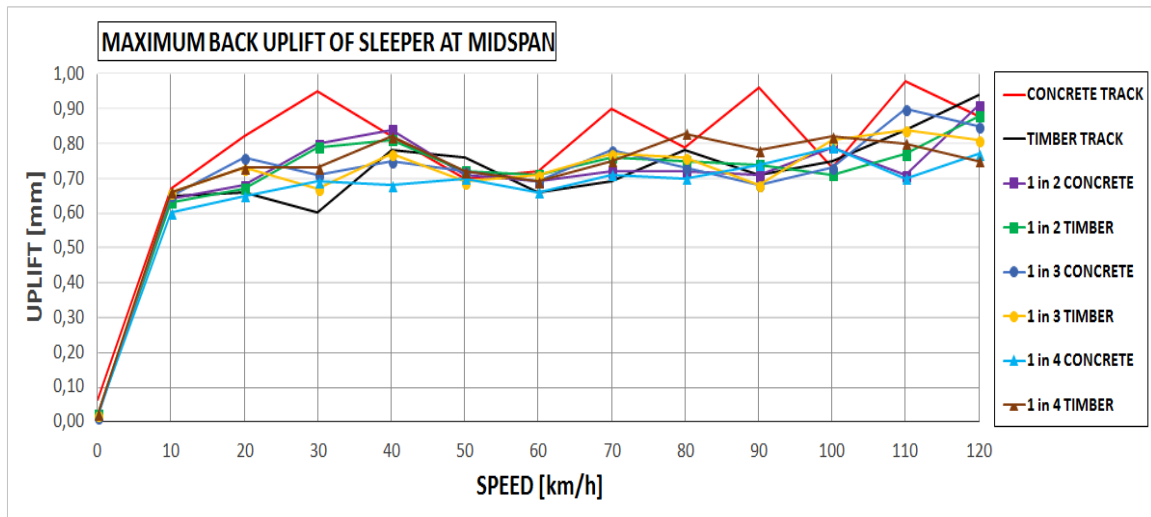
g) Maximum back uplift of sleeper under rail



h) Maximum displacement of sleeper at midspan

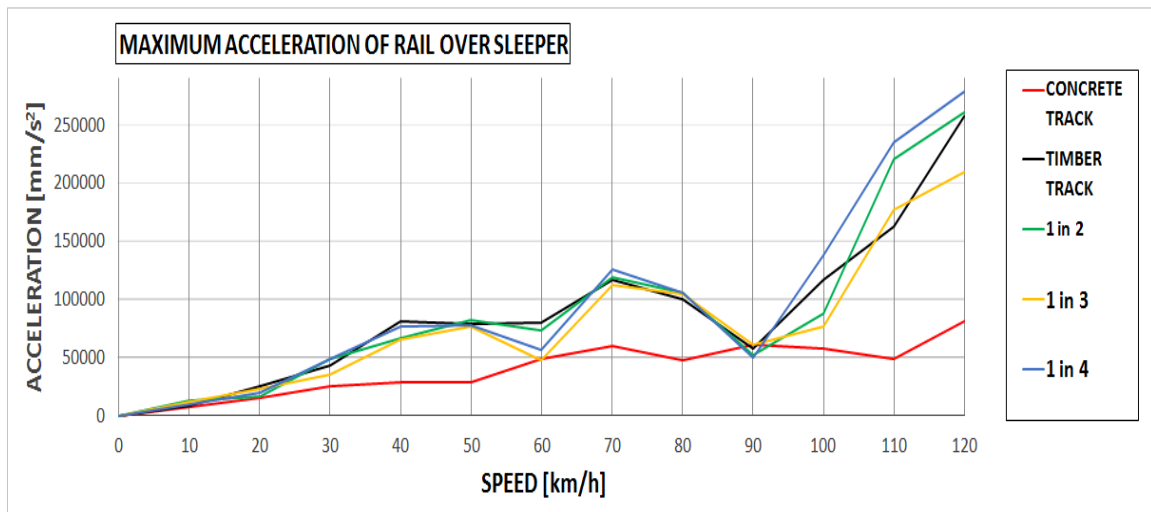


i) Maximum front uplift of sleeper at midspan

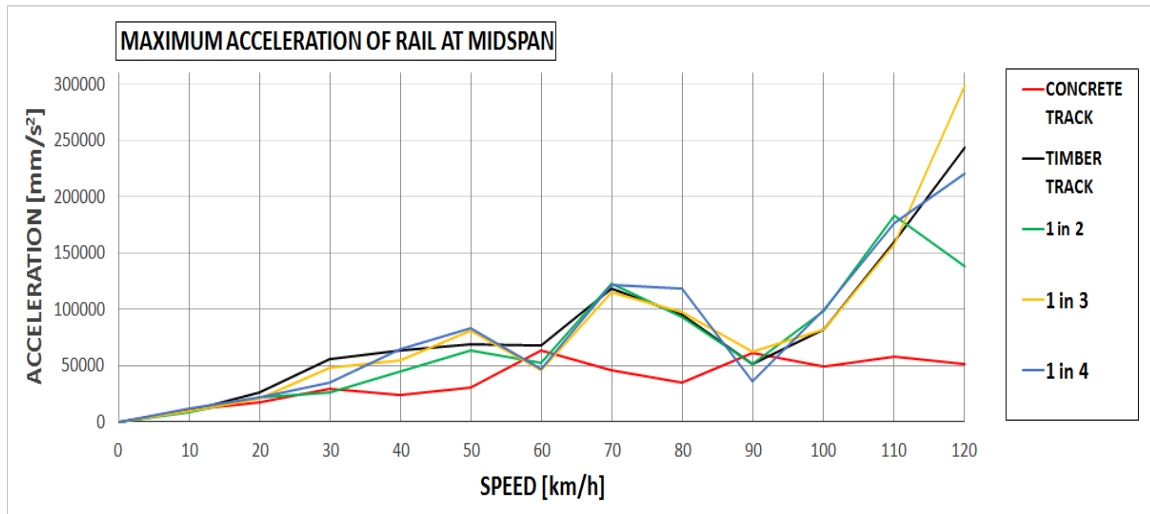


j) Maximum back uplift of sleeper at midspan

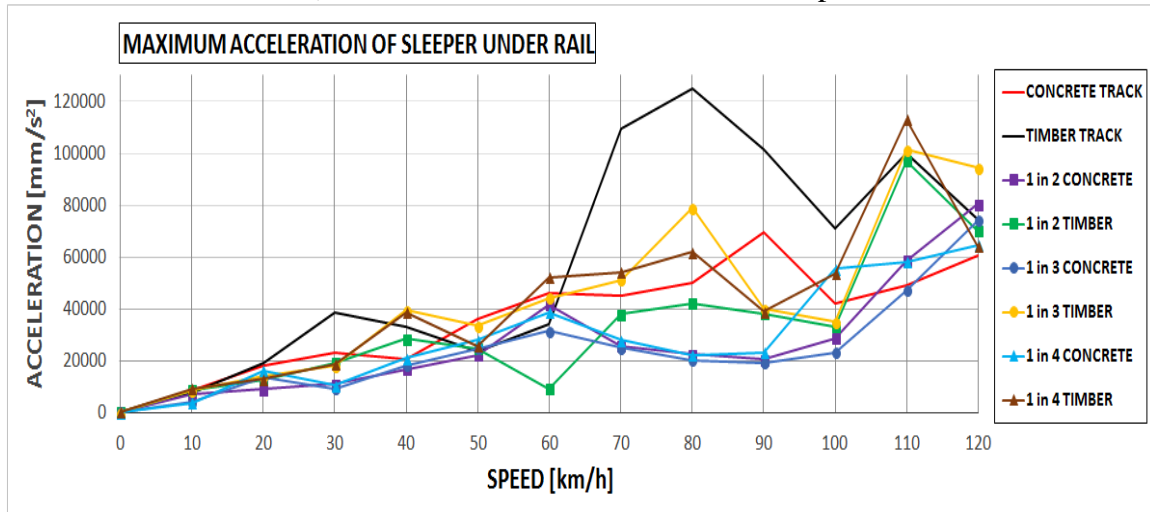
Fig. 4 Displacement responses of railway tracks under the moving load



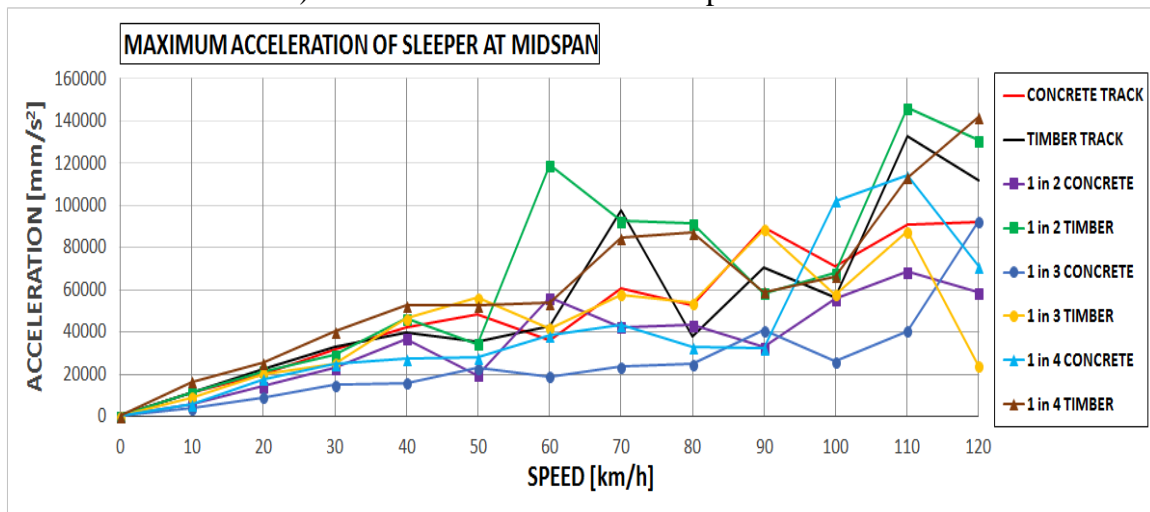
a) Maximum acceleration of rail over sleeper



b) Maximum acceleration of rail at midspan

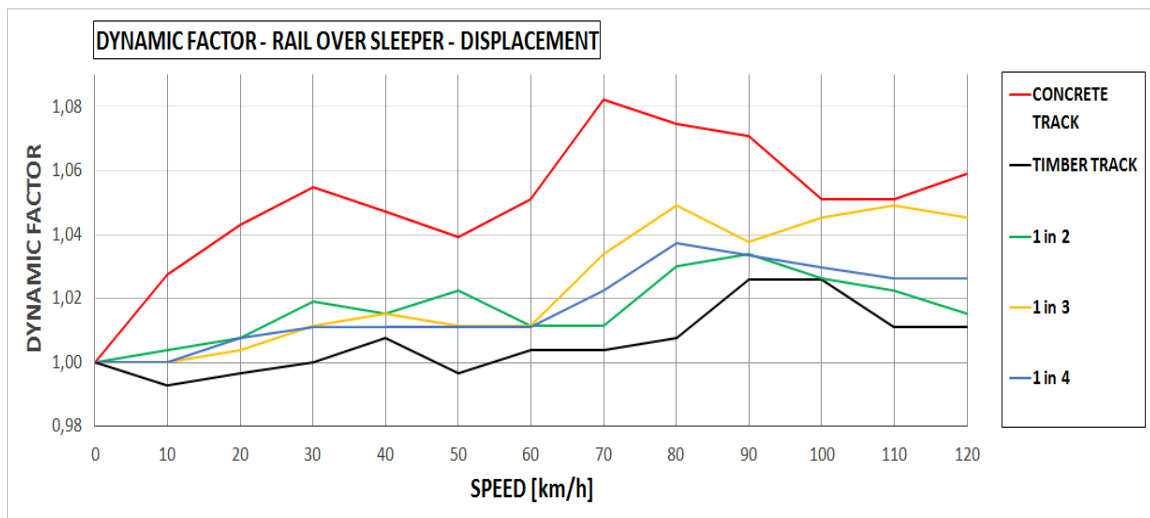


c) Maximum acceleration of sleeper under rail

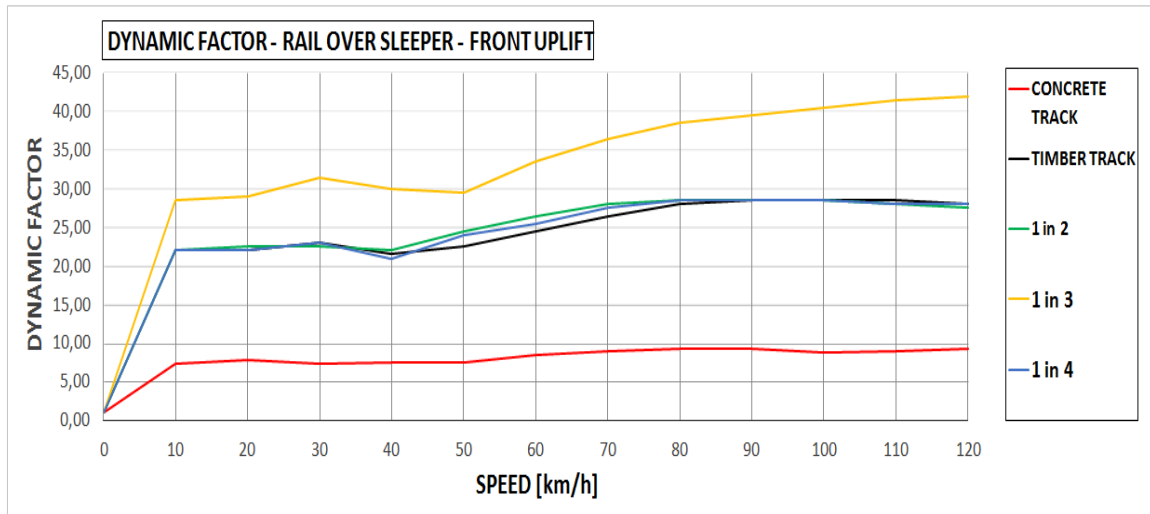


d) Maximum acceleration of sleeper at midspan

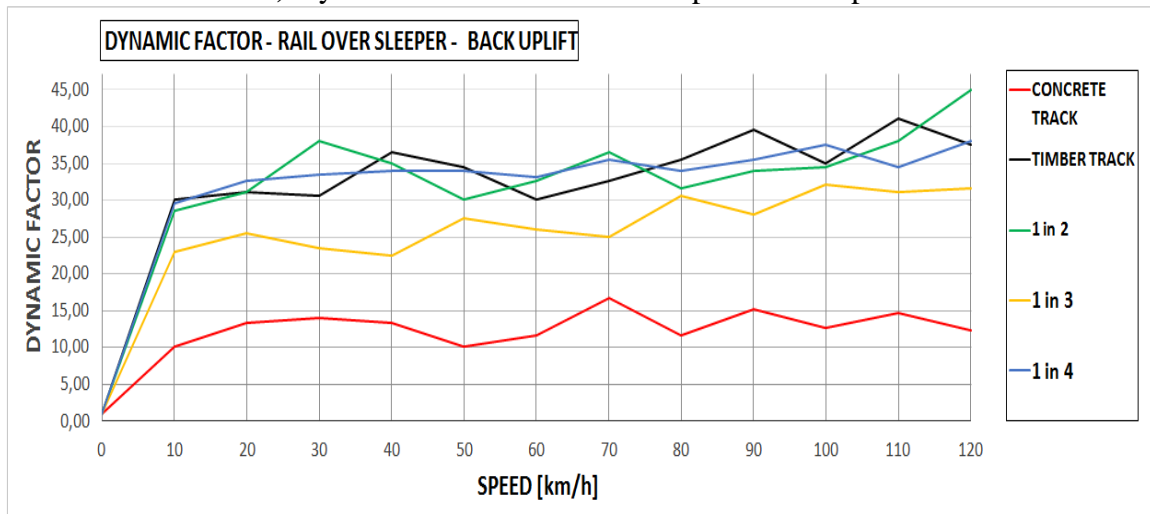
Fig. 5 Acceleration responses of railway tracks under the moving load



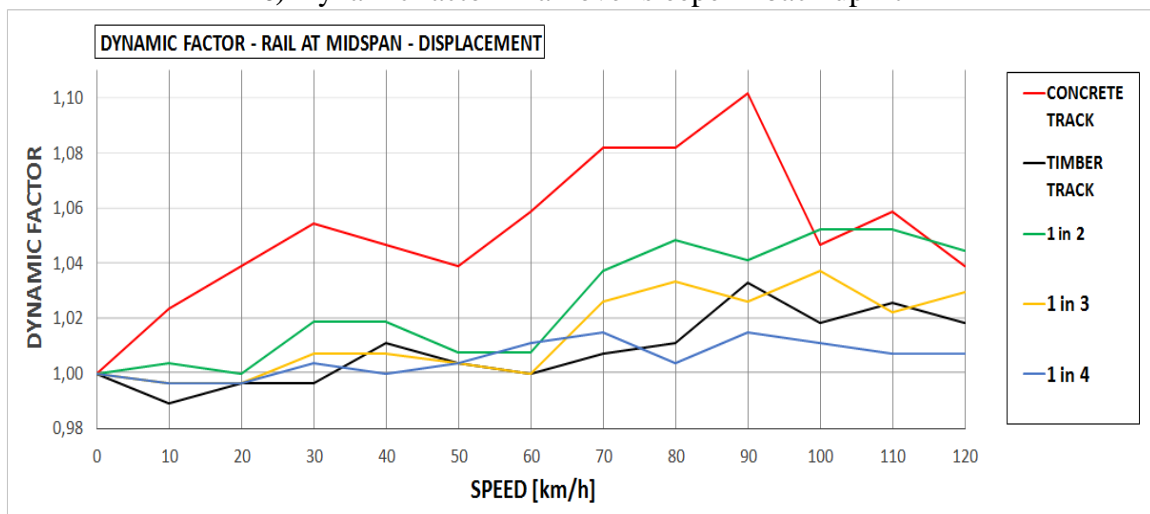
a) Dynamic factor – rail over sleeper – displacement



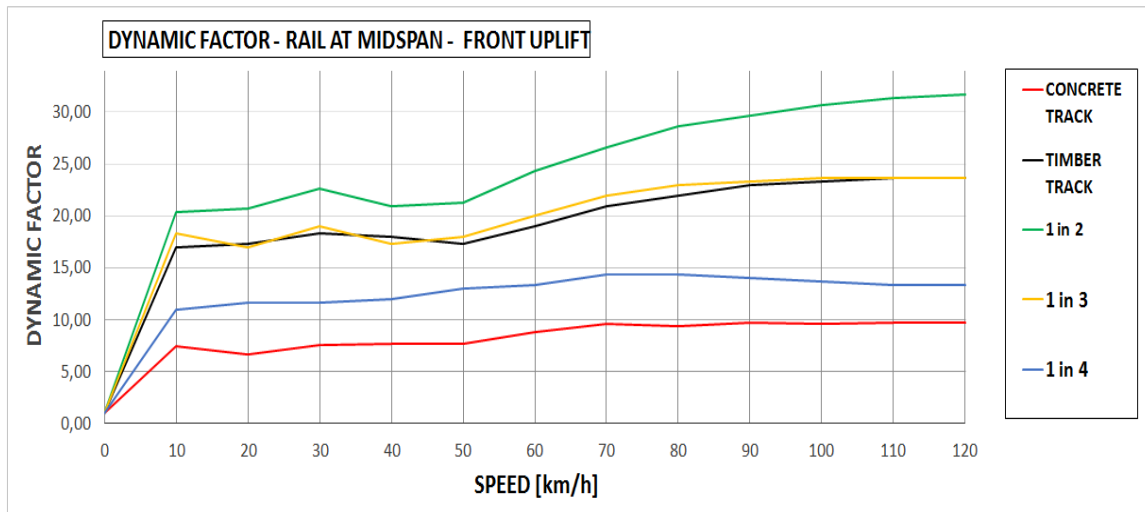
b) Dynamic factor – rail over sleeper – front uplift



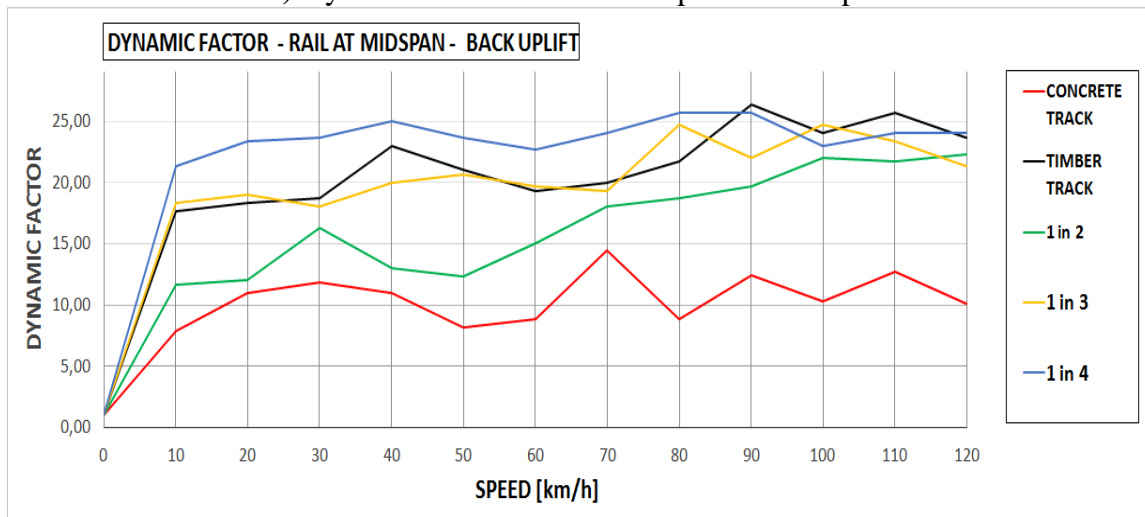
c) Dynamic factor – rail over sleeper – back uplift



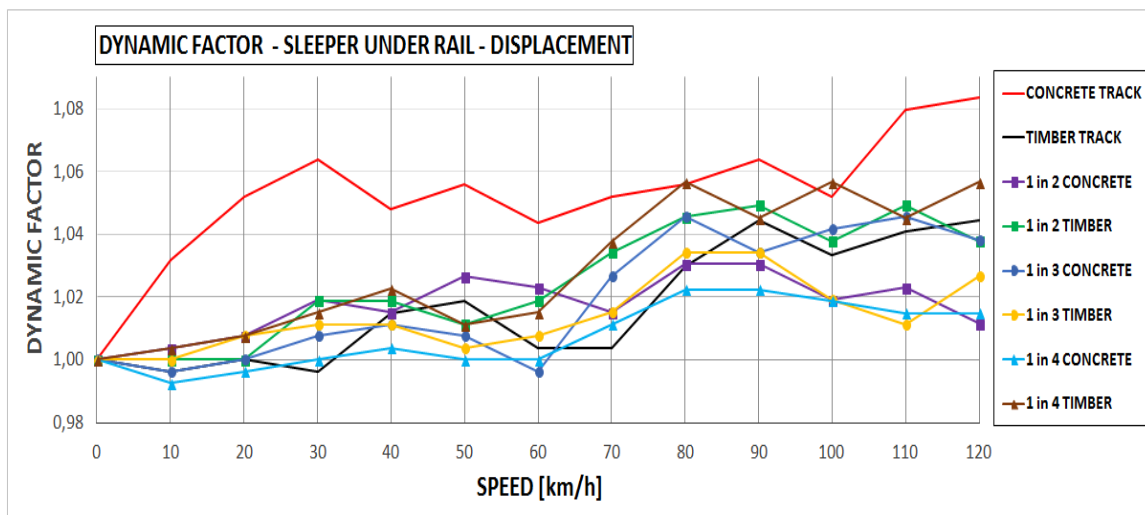
d) Dynamic factor – rail at midspan – displacement



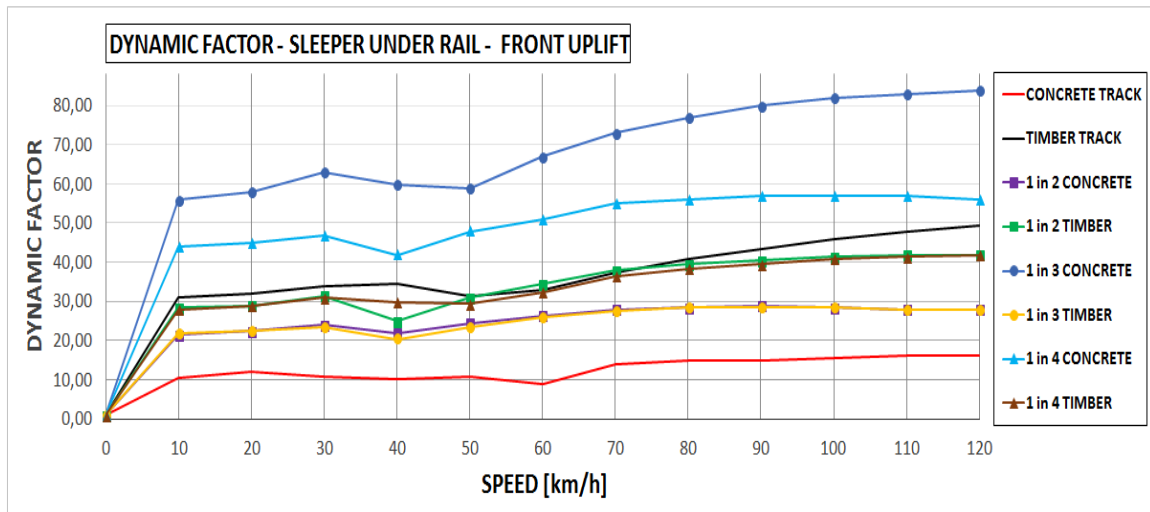
e) Dynamic factor – rail at midspan – front uplift



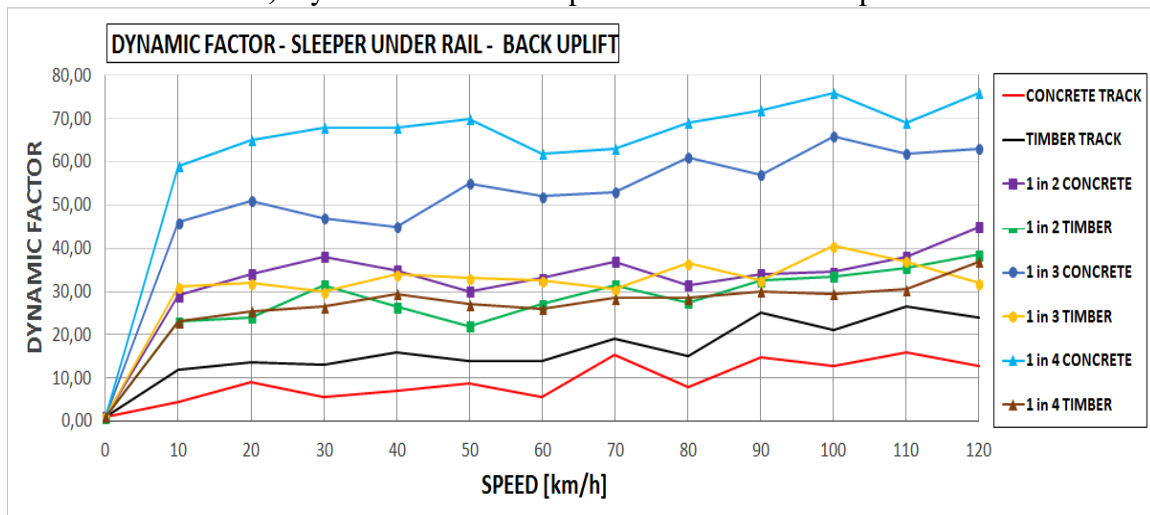
f) Dynamic factor – rail at midspan – back uplift



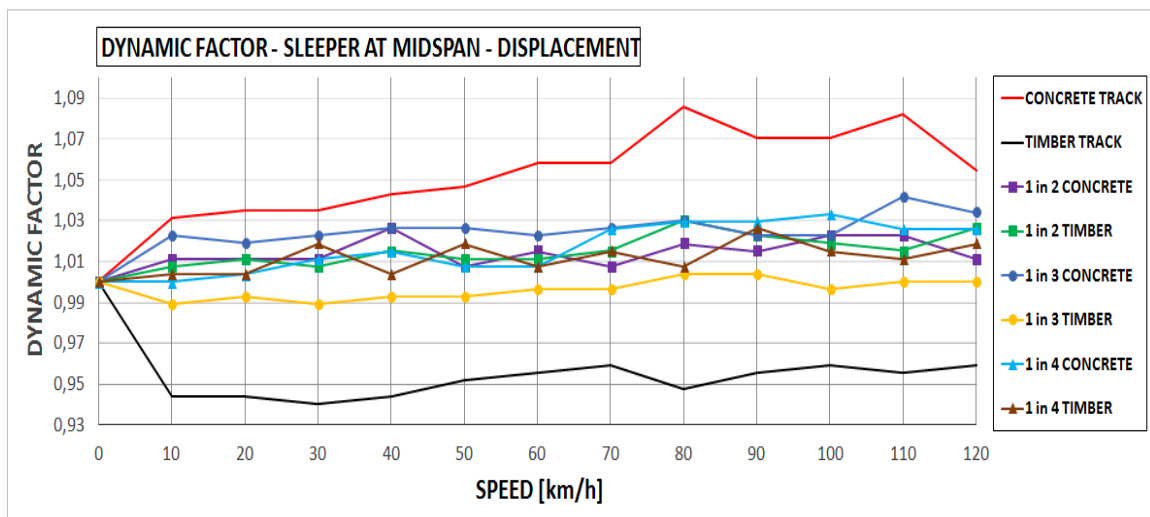
g) Dynamic factor of sleeper under rail



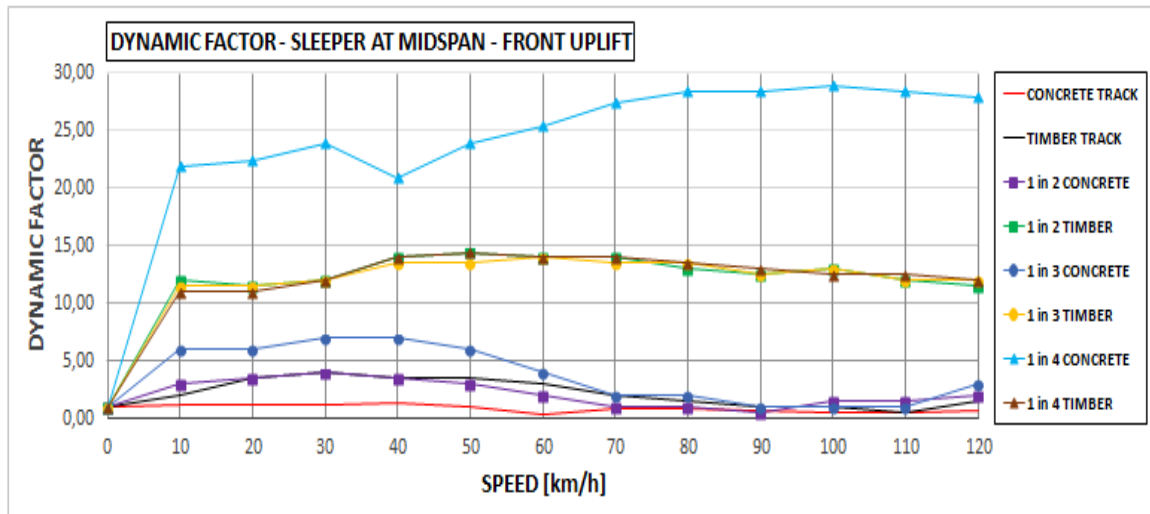
h) Dynamic factor – sleeper under rail – front uplift



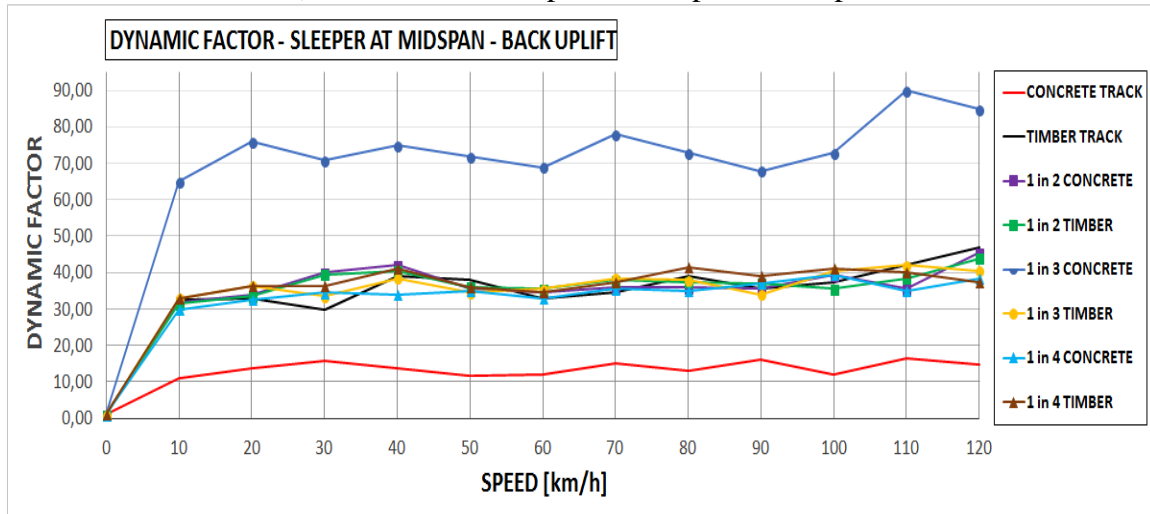
i) Dynamic factor – sleeper under rail – back uplift



j) Dynamic factor of sleeper at midspan



k) Maximum front uplift of sleeper at midspan



l) Dynamic factor – sleeper at midspan – back uplift

Fig. 6 Dynamic amplification phenomena of railway tracks under moving load